STRUCTURE OF THE UPPER MONTEREY SUBMARINE FAN VALLEY

James Sherrill Hamlin

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

STRUCTURE OF THE UPPER
MONTEREY SUBMARINE FAN VALLEY

by

James Sherrill Hamlin, Jr.

September 1974

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Thesis Co-Advisor: Dr. J. J. Von Schwind

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A secondary channel was observed beneath the western levee (right-hand levee looking downstream) of the Upper Monterey Submarine Fan Valley. It is believed that the Monterey Fan Valley and the secondary channel had different sources of sediment and that the secondary channel was deprived of its sediment supply approximately 1.9 million years ago.

The thickness of sediments overlying basement beneath the Fan Valley was found to be about 800 m.

Structure of the Upper
Monterey Submarine Fan Valley

by

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Seismic and 3.5 kHz acoustic reflection profiles were collected over the Monterey Submarine Fan Valley on two separate cruises. The 3.5 kHz profiles show the flatness of the channel bottom and the difference in levee heights on either side of the channel.

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I. INTRODUCTION

A. OBJECTIVES

Submarine fans are low angle cone-shaped deposits of sediments found at the mouths of submarine canyons. They are formed by sediment which has been transported down the canyons and constitute seaward continuations of these canyons. The valleys can be either depositional or erosional in nature and are of variable size and shape. They have winding courses with a tendency to hook to the left downstream in the Northern Hemisphere and often have ridges or levees along their sides. They generally lack tributaries but frequently have distributaries. Turbidity currents (dense flows of sediment-water mixtures) are believed to have an important influence in the formation of fan valleys. These currents are also the principle source of sediments to the submarine fans, which are dynamic areas of changing bathymetry due to the concentrated sedimentation associated with canyons. There is also evidence which suggests that submarine fans are part of geosynclines and will eventually be uplifted.

The main objective of this study was to determine the structure of the Upper Monterey Submarine Fan Valley (also called the Monterey Submarine Fan Channel in some references) using seismic reflection profiles.

B. SURVEY AREA DESCRIPTION

The Monterey Submarine Fan (Figure 1), covering an area of approximately 100,000 km^2, borders the continental slope off central California between Point

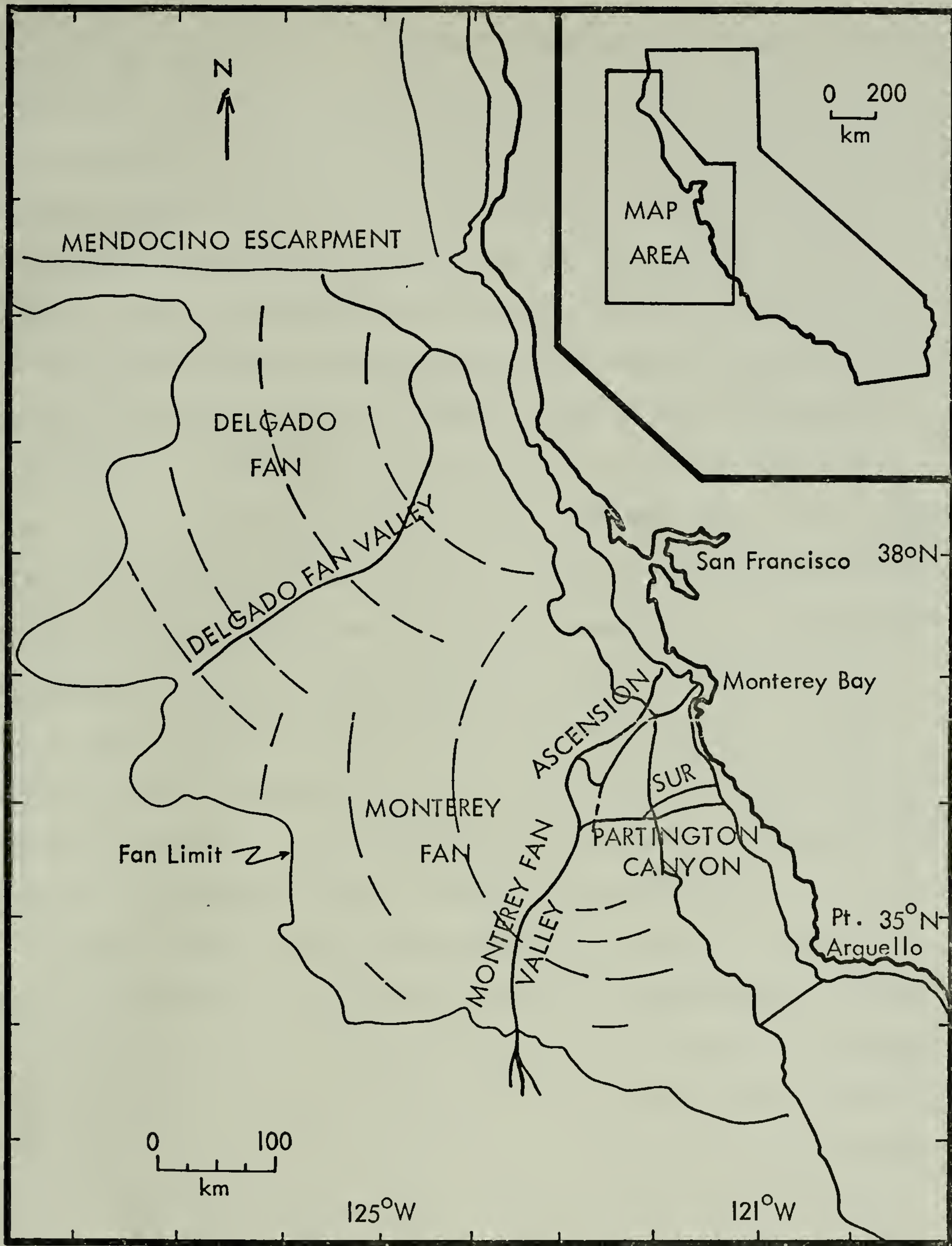

Figure 1 Survey Area (after Normark, (1969) and Wilde, (1965))

Arguello and San Francisco. The surface sediments are primarily green-grey mud (silt and finer) with occasional interbeddings of dark, very fine sand layers, 1 to 2 cm thick, that have a muddy matrix, indicating periodic transportation by turbidity currents. The continental aspect of the crust underlying the Monterey Fan was shown by Woollard and Strange (1962). They found that over the fan areas off the central California coast the measured free-air gravity anomaly was more than 20 mgal less than the free-air gravity anomaly assumed for isostatic equilibrium. The gravity-derived depths of the M-discontinuity are about 2 km greater than those determined by seismic work. This, coupled with the lower mean seismic velocities found in the region, indicates a crust of lower density than the typical oceanic crust. Wilde (1965) determined the extent of the fan and the sources of the sediments. His research represents one of the few documented examples of modern sediments of the greywacke type. He also determined the maximum age of the fan to be 30 - 40 million years (Early Oligocene), assuming present rates of sedimentation, with a volume of 3.7×10^{13} m^3.

Normark (1969), using seismic reflection profiling to study the Monterey Submarine Fan, described three major canyon systems tributary to the fan; the Lucia-Partington-Sur Canyons, the Ascension Canyon, and the Monterey-Carmel Canyons (Figure 1). He also described the Monterey Submarine Fan Valley, the seaward continuation of the Monterey Submarine Canyon. The valley extends about 300 km south-southwest across the entire fan and has, located at 36^{o} 15' N and 122^{o} 40' W, the only known horseshoe meander in a submarine fan valley. There are depressions in the San Lucas Fan located off the tip of Baja California, however, that appear to have been, in the past, horseshoe meanders (Normark, 1969).

Shepard (1966) documented this meander and hypothesized that it might be related to some subsurface structure such as a coarse sediment zone.

The Monterey Submarine Fan Valley has well developed levees throughout most of its length. These levees are caused by turbidity currents overflowing the channel and are best developed in the meander itself, gradually decreasing in height further downstream. By convention in this paper the levees will be described relative to the downstream orientation. Komar (1969) described the processes of turbidity current flow in submarine channels:

> "A turbidity current that is confined to a channel will have a cross-channel surface slope owing to a combination of the Coriolis force (Menard, 1955) and centrifugal force whenever the channel is curving. In the Northern Hemisphere, Coriolis tends to cause an upward slope across the channel to the right (looking down the channel). If the channel curves to the right, the Coriolis and centrifugal forces are opposed. If the centrifugal force exceeds the Coriolis force, the interface may slope upwards to the left."

Downstream from the meander the channel exhibits the left-hand hook described by Menard (1955). Here it will have a tendency to be diverted to the left due to the fact that the left-hand levee is lower than the right-hand levee.

In the upper fan, the Ascension Fan Valley intercepts the Monterey channel below the meander as a hanging valley. Normark (1969) suggested that the lower half of the Ascension channel was pirated by the Monterey channel and left as a hanging valley by subsequent downcutting.

As mentioned previously, a turbidity current in a confined channel will have a cross-channel slope. An equation can be developed that relates the pressure, Coriolis and centrifugal forces for this situation. Komar (1969) in applying this equation to the Monterey Submarine Fan Valley morphology for a channel-full flow obtained current speeds ranging from 600 cm/sec to 2000 cm/sec as functions of the channel-axis slope, the

radius of curvature of the channel, the cross-channel slope, and the density of the current. He also determined that a channel-full flow contained in excess of 10^8 to 10^9 m^3 of sediment. It is suggested by Ewing et al. (1970) that 10^5 m^3 is the minimum volume for a submarine slump which will generate a self-sustaining turbidity current capable of traversing the entire fan. The time of passage of a turbidity current is directly related to its volume and velocity. For a typical cross-section of the Monterey Submarine Fan Valley, the time of passage might range from 5 to 30 min for flow lengths of 3 to 30 km respectfully.

Komar (1973) found that a reasonable decrease in the channel-axis slope could cause the flow thickness to double, and, if dilution of the suspension current occurs, the thickness could increase by a factor of four or more. This could explain the systematic increases in the relief of many submarine channels along their lengths.

The Monterey Submarine Fan Valley is not unique. Most of the submarine fan valleys around the world such as the Indus, Magdalena, Astoria, Hudson, La Jolla, Congo, and Cascadia Channels have levee height differences to some degree. Most of the channels also have meandering courses similar to subaerial streams, though not as well developed as the horseshoe meander, and,in the Northern Hemisphere, exhibit a left-hand hook except where their courses are restricted by topography.

II. COLLECTION OF DATA

A. EQUIPMENT

The data was collected on two separate cruises. The first cruise, cruise 1204-74 (November 1973), was aboard the USNS DESTEIGUER (T-AGOR 12), and the second, cruise 1212-74 (April 1974), was aboard the USNS BARTLETT (T-AGOR 13). The 3.5 kHz acoustic source used for normal reflection profiling for both cruises was manufactured by Ocean Research Equipment, Inc., and was hull mounted amidships at the keel. The 3.5 kHz records accurately depict the bottom topography and show a subbottom penetration to about 80 m. The seismic source, used for both cruises, was a Teledyne 30-kJ sparker system. On the DESTEIGUER, the firing rate was 4 sec, with the low-pass filter set at 100 Hz and the high-pass filter set at 31 Hz. On the BARTLETT, a 10 sec firing rate was utilized, with a high-pass filter set at 25 Hz and the low-pass filter at 98 Hz. A Bisset-Berman STD was used on the DESTEIGUER to determine the sound speed profile to a depth of 1000 m; on the BARTLETT, XBT casts were made to determine the temperature profiles.

The 3.5 kHz and seismic reflection records were hand annotated as to ship course and speed, time (noted each 15 min), track number, and the full-record time scale.

B. SELECTION OF TRACKS

The cruises were planned to cover the Monterey Submarine Fan Valley from the mouth of the canyon to below the horseshoe meander. In all cases, the lines (Figure 2) were taken as nearly perpendicular to the

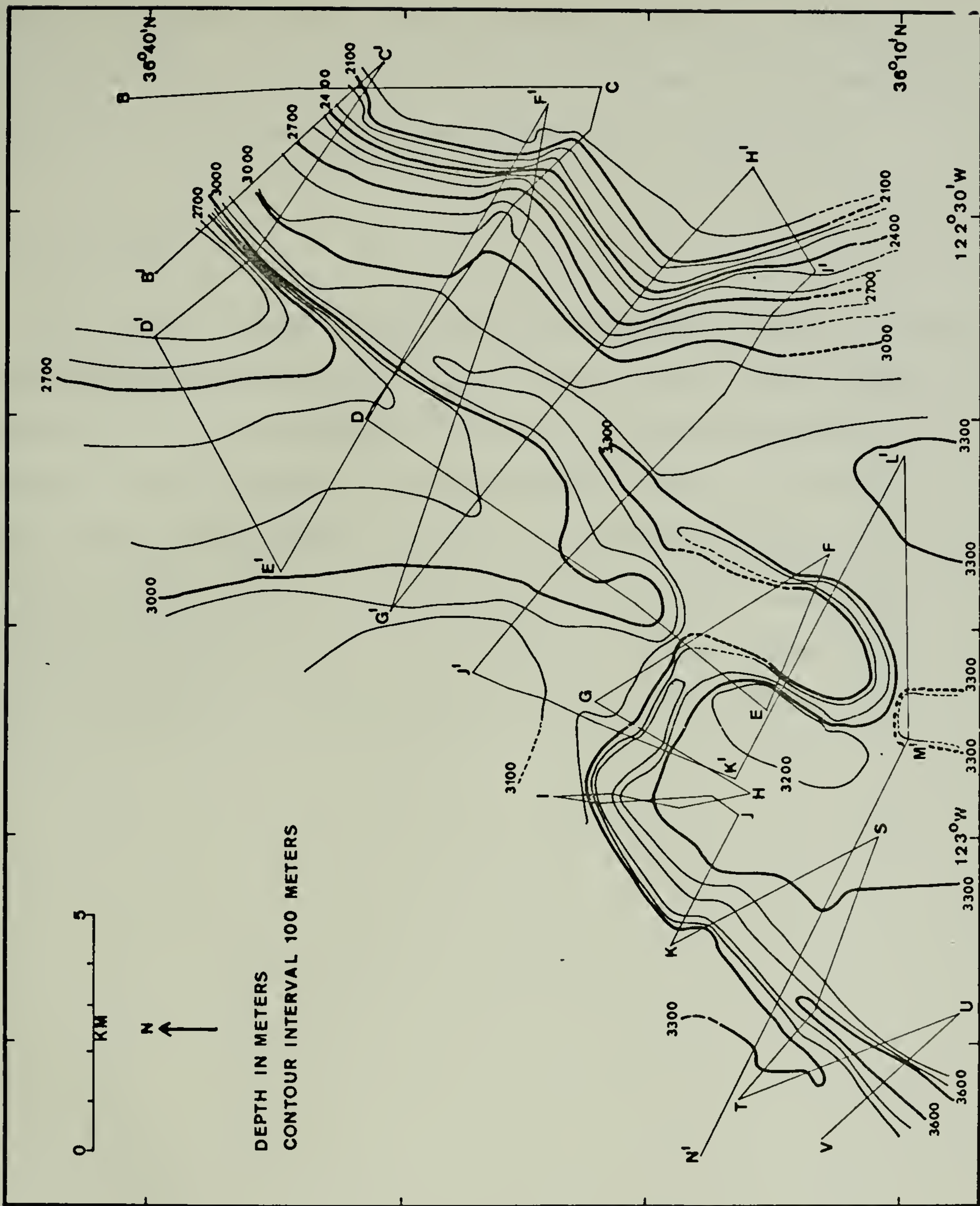

Figure 2 Bathymetric chart of the area and ship's tracks. The primed letters refer to the USNS Bartlett Cruise and the unprimed letters refer to the USNS Desteiguer Cruise.

channel axis as possible in order to reduce the effects of reflections from bottom slopes to either side of the ship's track line (sideswipe). A speed of 6 to 8 kt was maintained throughout the survey area.

C. NAVIGATION

The navigation for both cruises was primarily by satellite. Fixes were obtained at irregular intervals of about 90 min. Since the ship was too far out at sea for radar, and since only one loran line was available, dead reckoning was used between the fixes. At the end of each cruise the navigation was reworked to determine the ship's track as accurately as possible. This reworking consisted of comparing the bathymetry obtained from the ship's fathometer to the bathymetry of HO Chart 5402 along with the satellite fixes and the available loran lines.

III. DATA ANALYSIS AND DISCUSSION

A. CONSTRUCTION OF BATHYMETRIC CHART OF THE AREA

The first step in the analysis of data was to determine a sounding speed to enable construction of a bathymetric chart of the area. The Bisset-Berman STD was utilized to obtain a sound speed profile for the upper 1000 m of the water column. Below 1000 m, the water was considered to be isothermal, with pressure the only factor contributing to an increase in sound speed. Values for sound speed from 1000 m to 3000 m were taken from tables of Wilson's equation (U.S. Naval Oceanographic Office, 1966), and averaged with the STD sound speeds to obtain a sounding speed of 1493.4 m/sec for a depth of 3000 m. It is expected that the depths are accurate to $\pm$ 1 m at 3500 m.

The same average sound speed was used to analyze the data from both cruises. It is not felt that this caused a large error in the results since the sounding speed in the area of interest should be approximately the same throughout the year. Also, the calculated depths of the two cruises correlated very well.

The two-way travel time of the sound in seconds was measured on the 3.5 kHz records using a Gerber Variable Scale and plotted on HO Chart 5402 (scale 1:210,668) at 100 m contour intervals (Figure 2). The decision to adopt 100 m intervals was based on a desire to depict the greatest detail while still maintaining the general trend.

This bathymentric chart was constructed largely independent of Shepard's (1966) bathymetric chart of the area. Six positions, two above the meander, two in the meander, and two below the meander were randomly selected for comparison between the author's chart and Shepard's

chart. The depths of the two points in the meander agreed exactly; the maximum difference in the depths outside the meander was 10 m. Since neither chart is consistently shallower or deeper than the other, and the magnitude of the differences is relatively small, it is not felt that any inferences can be made concerning erosion or deposition in the Monterey Fan Valley from 1965 to present. The depth differences are probably due to imprecise navigation.

Further analysis of the 3.5 kHz records shows the flatness of the channel axis with average gradients of 10 m/km above the meander, 5.7 m/km in the meander, and 2.7 m/km below the meander. The largest levee, found on the convex side of the meander (the left-hand levee), is 367 m above the channel floor. This compares with a right-hand levee of 338 m above the channel axis above the meander and 307 m above the channel axis below the meander. The levee profile is very irregular with a series of rises and sags. The largest sag occurs near the southern extreme of the meander and connects it with a discontinuous valley, the Monterey East Fan Valley (the dotted line extending south from the horseshoe meander in Figure 1) (Shepard, 1966).

B. SECONDARY CHANNELS

Crossings B'-C' (Figure 3) and C'-D' (Figure 4) both show a relatively small channel buried below the right-hand levee of the Monterey Submarine Fan Valley at a sediment depth of 155 m. This depth was determined using a mean sediment speed of 1671 m/sec. To arrive at the sounding speed, the surface sediment sound speed was assumed to be 1593 m/sec and a linear sound speed gradient of 1 m/sec/m was assumed (Hamilton, 1969). The assumption of a linear sound speed gradient is good at shallow depths, but not at greater depths since curves of sound

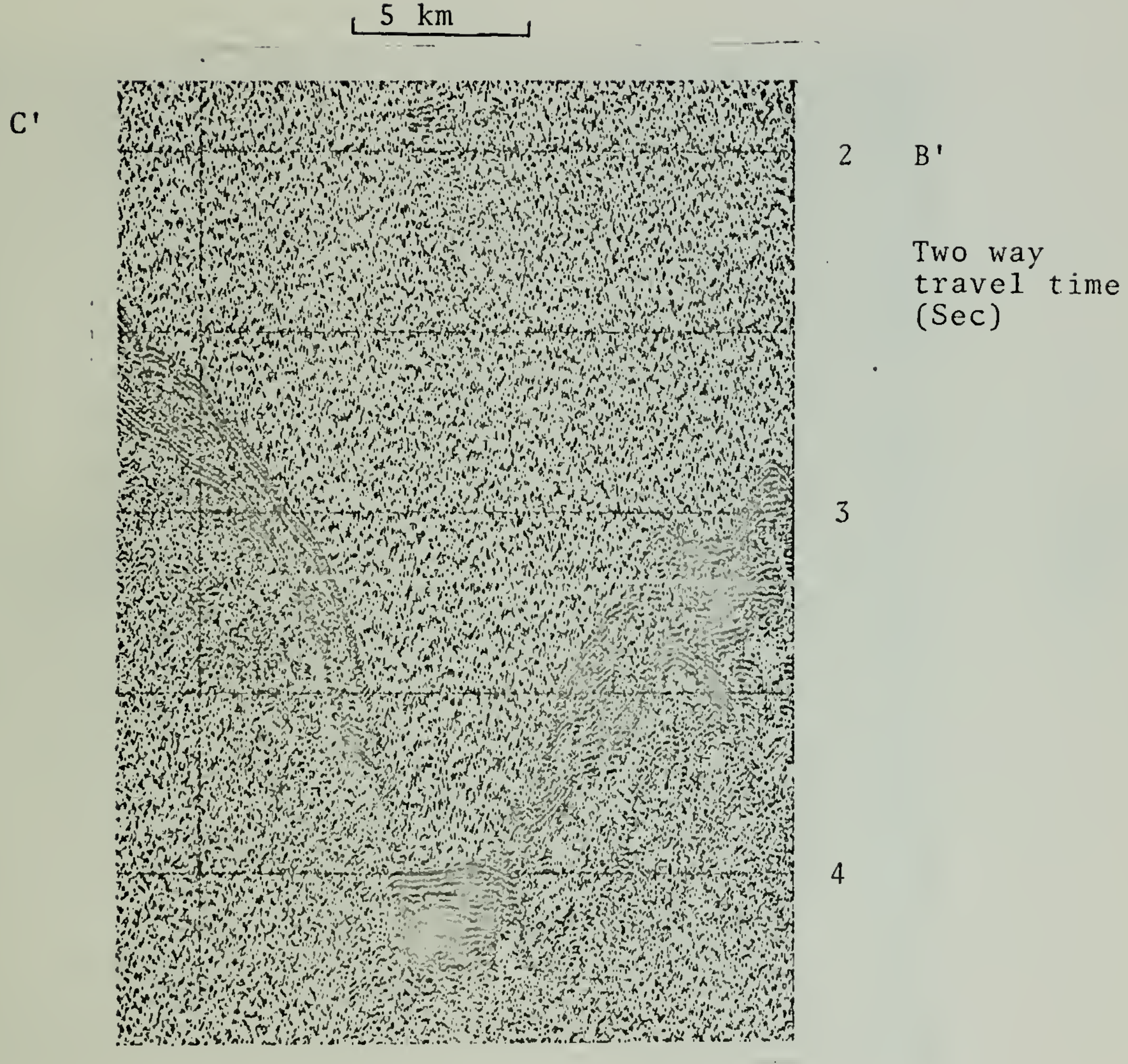

Figure 3 Seismic Reflection Profile B'-C'

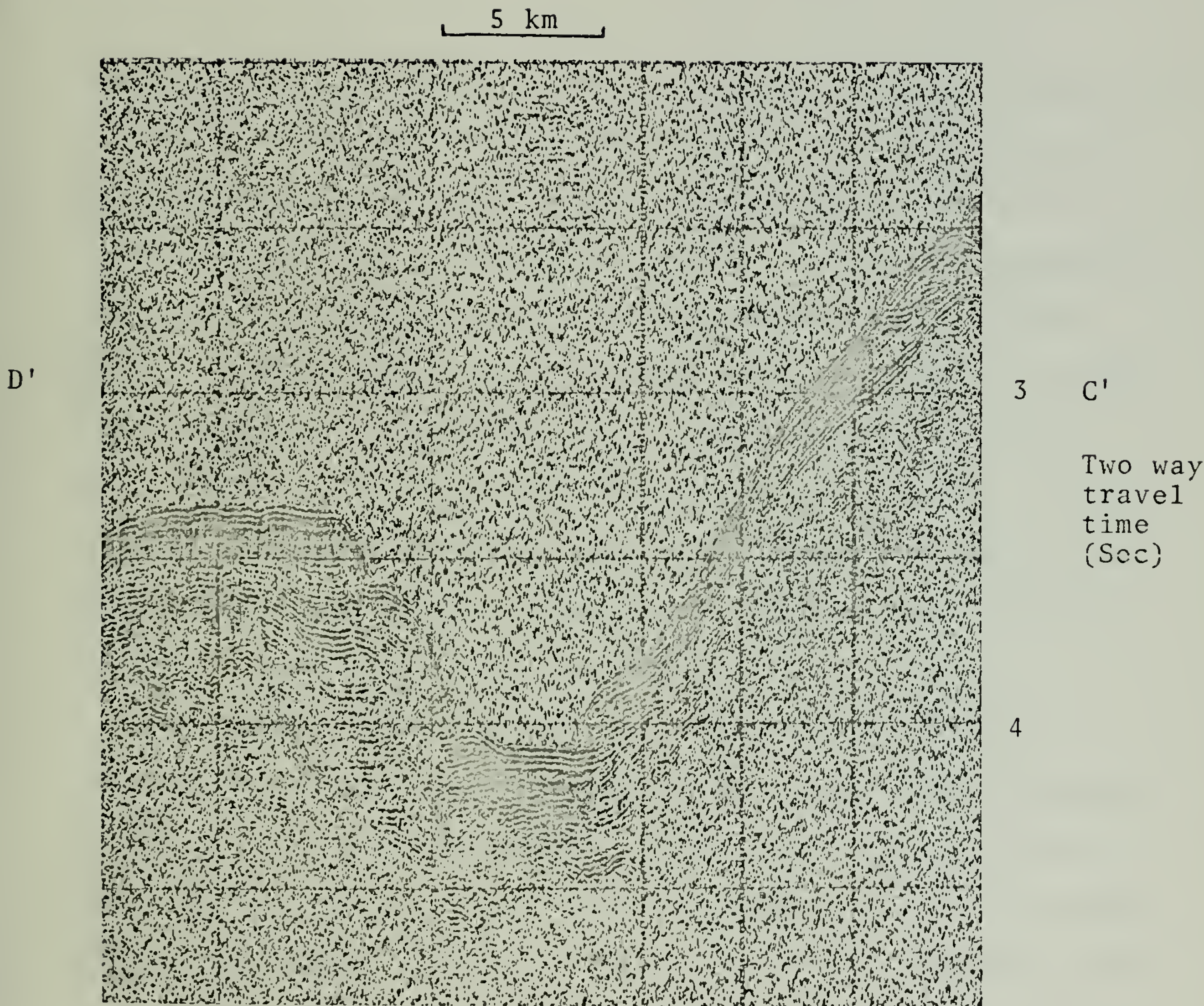

Figure 4 Seismic Reflection Profile C'-D'

speed vs. depth are parabolic at the greater depths (Hamilton, 1969). This channel also appears in crossing E'-F' (Figures 5 and 6), but it is smaller and not as distinct. Because the axis of the buried channel is shallower than the main channel axis and the Monterey Fan Valley in this region is depositional, the buried channel probably does not represent an earlier course of the fan valley, but rather a secondary one.

Due to the secondary channel being below the present western levee of the Monterey Fan Valley, it is believed that when this channel was active the fan valley was already well formed. The Monterey Submarine Canyon was probably not the sediment source of the secondary channel since a turbidity current flowing down the canyon would tend to continue down the Monterey Submarine Fan Valley and not initiate a new channel. It is also not likely that the secondary channel was formed by turbidity currents overflowing the western levee since the overflow would probably have occured along the entire stretch of the valley where the secondary channel is seen and not just at its head.

The secondary channel was deprived of its source of sediment at some time in the past, possibly due to a change in the drainage patterns of the coastal region. This change could have been caused by faulting since the region is seismically active. Knowing the depth of the channel (155 m) and assuming a rate of sedimentation of 8 cm/1000 yr (Wilde, 1965), the age of the channel can be estimated to be 1.9 million years. This age is a maximum since the actual sedimentation rate was probably greater than that assumed.

No other secondary channels were observed in the records.

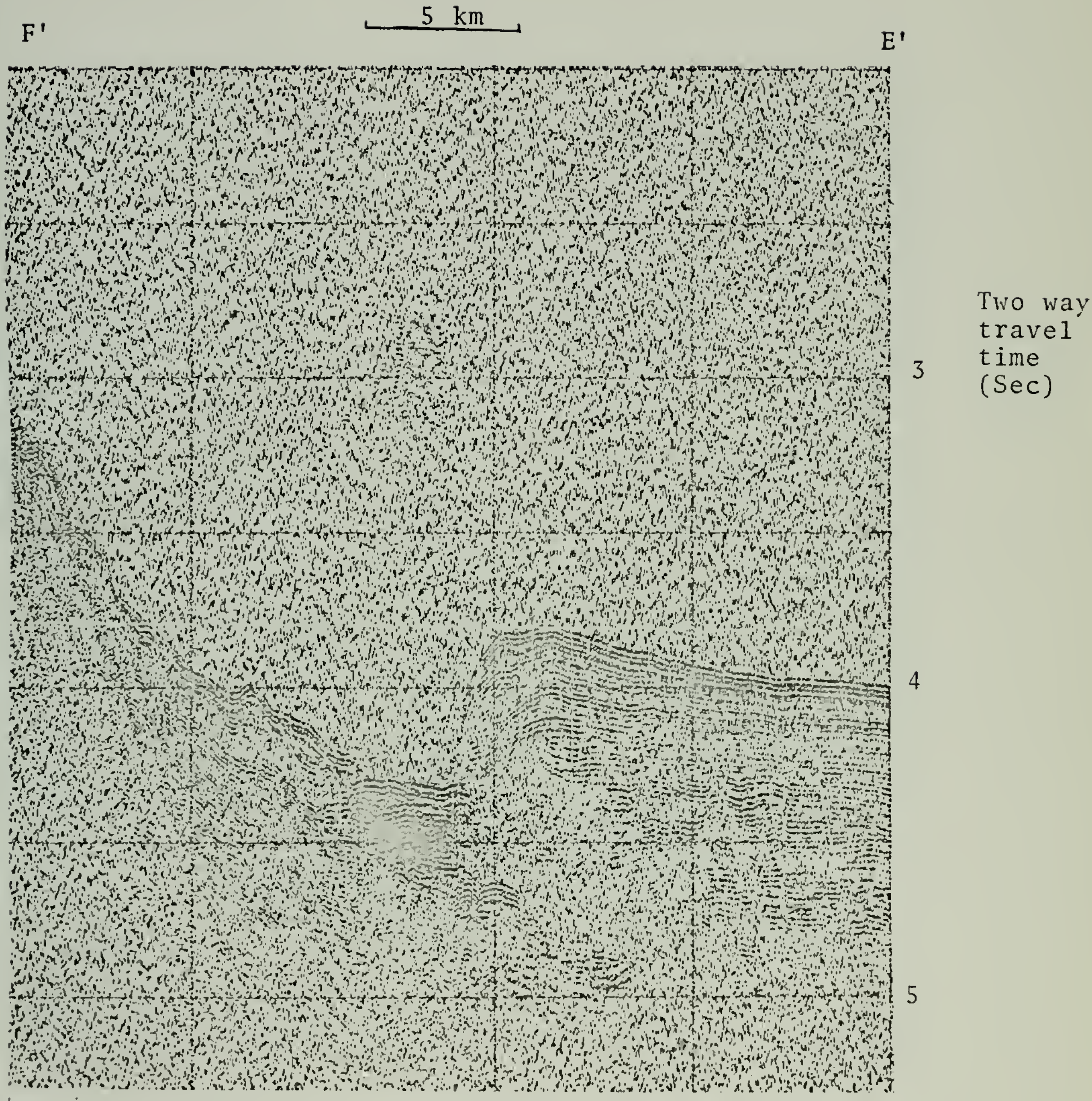

Figure 5 Seismic Reflection Profile E'-F'

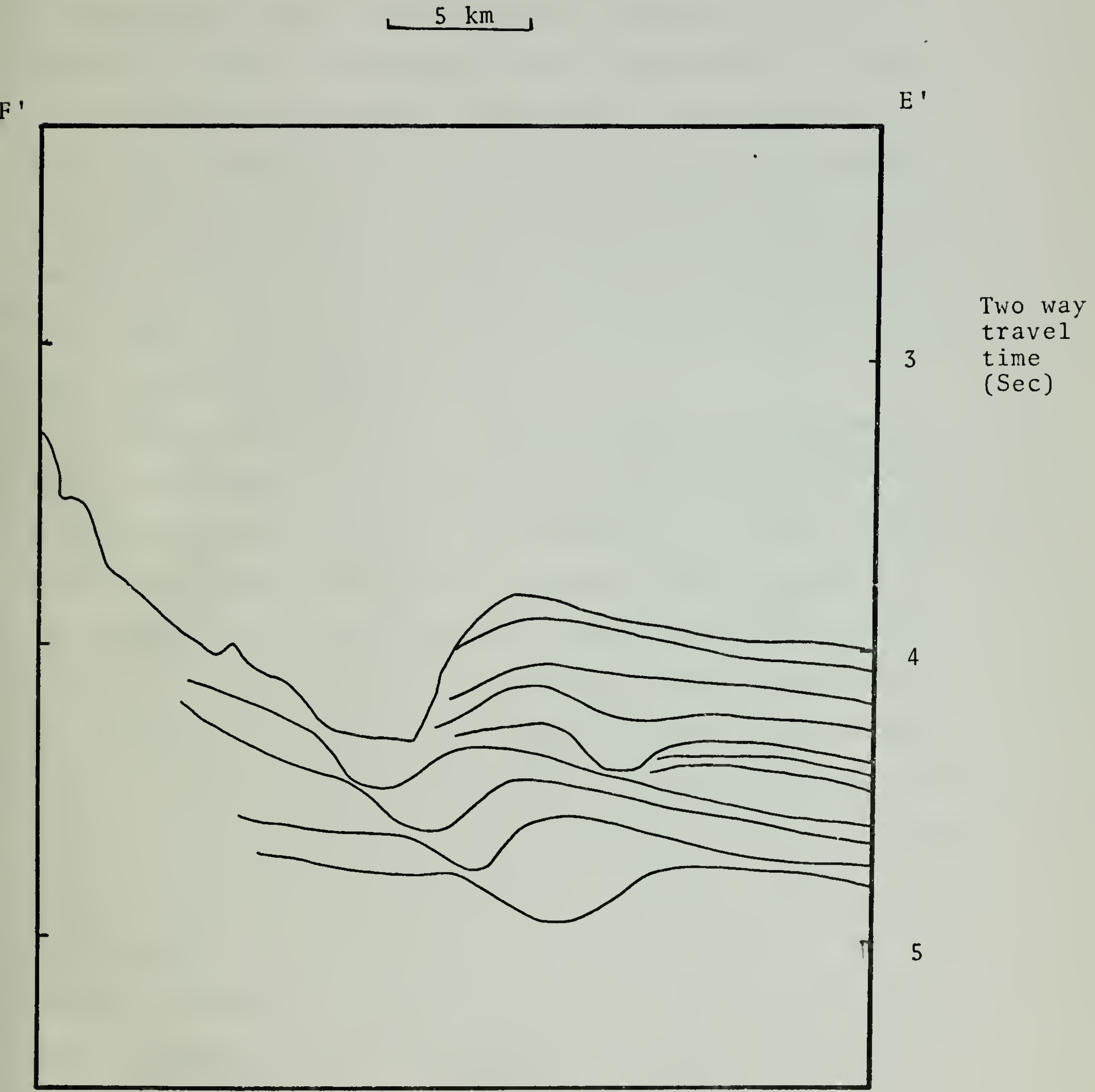

Figure 6 Interpretive Drawing of Seismic Reflection Profile E'-F'

C. CHANNEL MIGRATION

The Monterey Submarine Fan Valley turns southward (to the left) almost at its head. It is believed that the initial impetus for this left-hand hook was the presence of the Ascension Fan Valley, and not a levee height difference. A turbidity current flowing out the Monterey Submarine Canyon would have turned to the south to flow parallel to the contours. It would not have been able to continue west or turn to the north (right) because that would have meant the current would be flowing uphill towards the Ascension Fan Valley.

Starting with crossing E'-F' (Figures 5 and 6) (also crossing G'-H', Figure 13) and continuing downstream, most of the seismic profiles show a migration of the channel axis to the southeast (to the left downstream). One of the crossings, however, I'-J' (Figure 7), shows a migration to the northwest (to the right downstream) with a later migration to the southeast. Another section, J'-K' (Figure 8), located downstream of the horseshoe meander, shows only a channel migration to the northwest. In all of these cases the records indicate a continuous migration of the Monterey Submarine Fan Valley to its present location from an initially deeper position, i.e., channel migration by deposition. The cross-channel slope of a turbidity current in a confined channel causes preferential sedimentation, and because of this, the right-hand levee is generally higher than the left resulting in the channel being diverted to the left as originally suggested by Menard (1955).

Subaerial streams with light bed loads have two methods of adjusting their gradients; they may either cut into the stream beds at their heads, or lengthen their courses by becoming more sinuous. Either of these processes decreases the slope of the stream. If the stream is

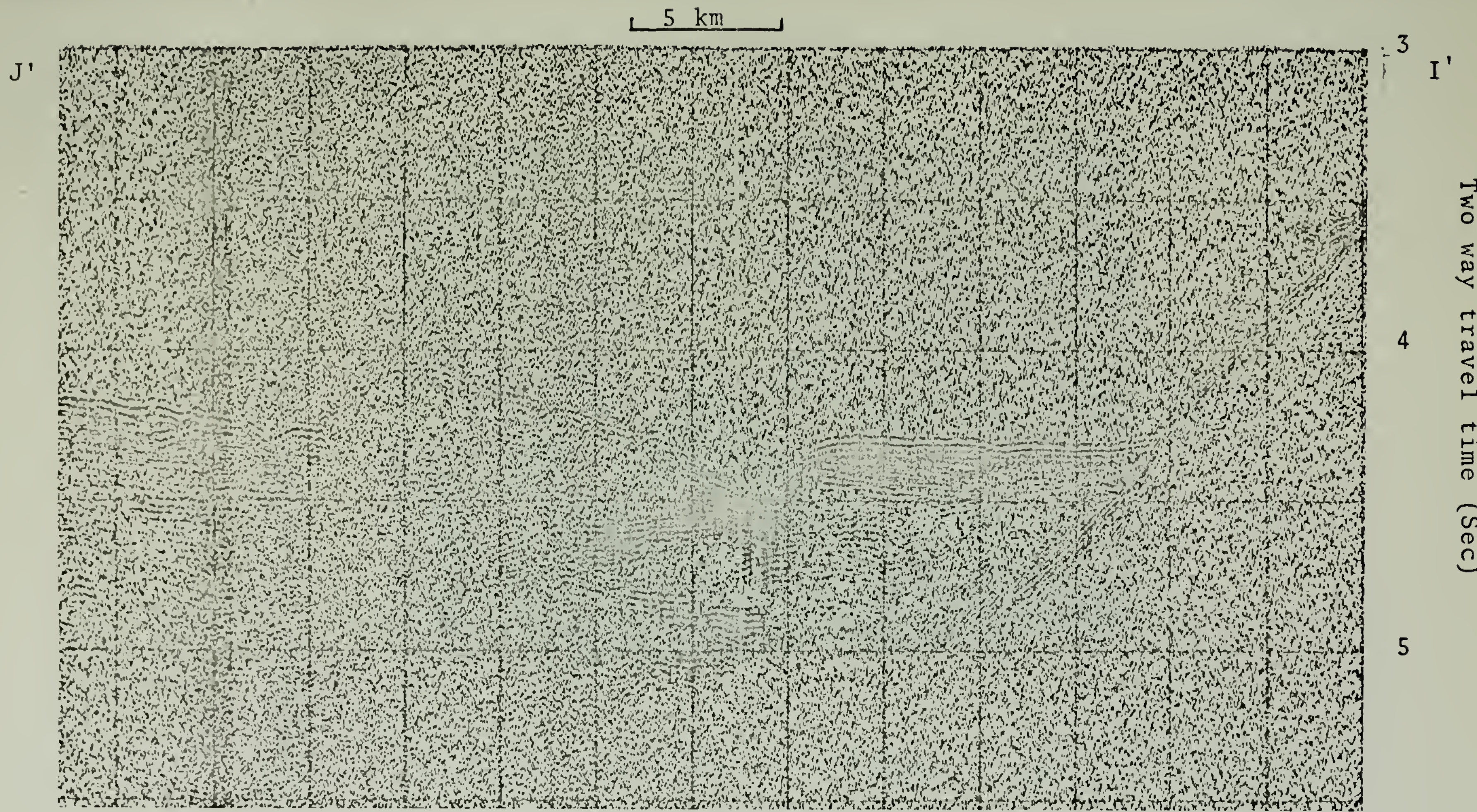

Figure 7 Seismic Reflection Profile I'-J'

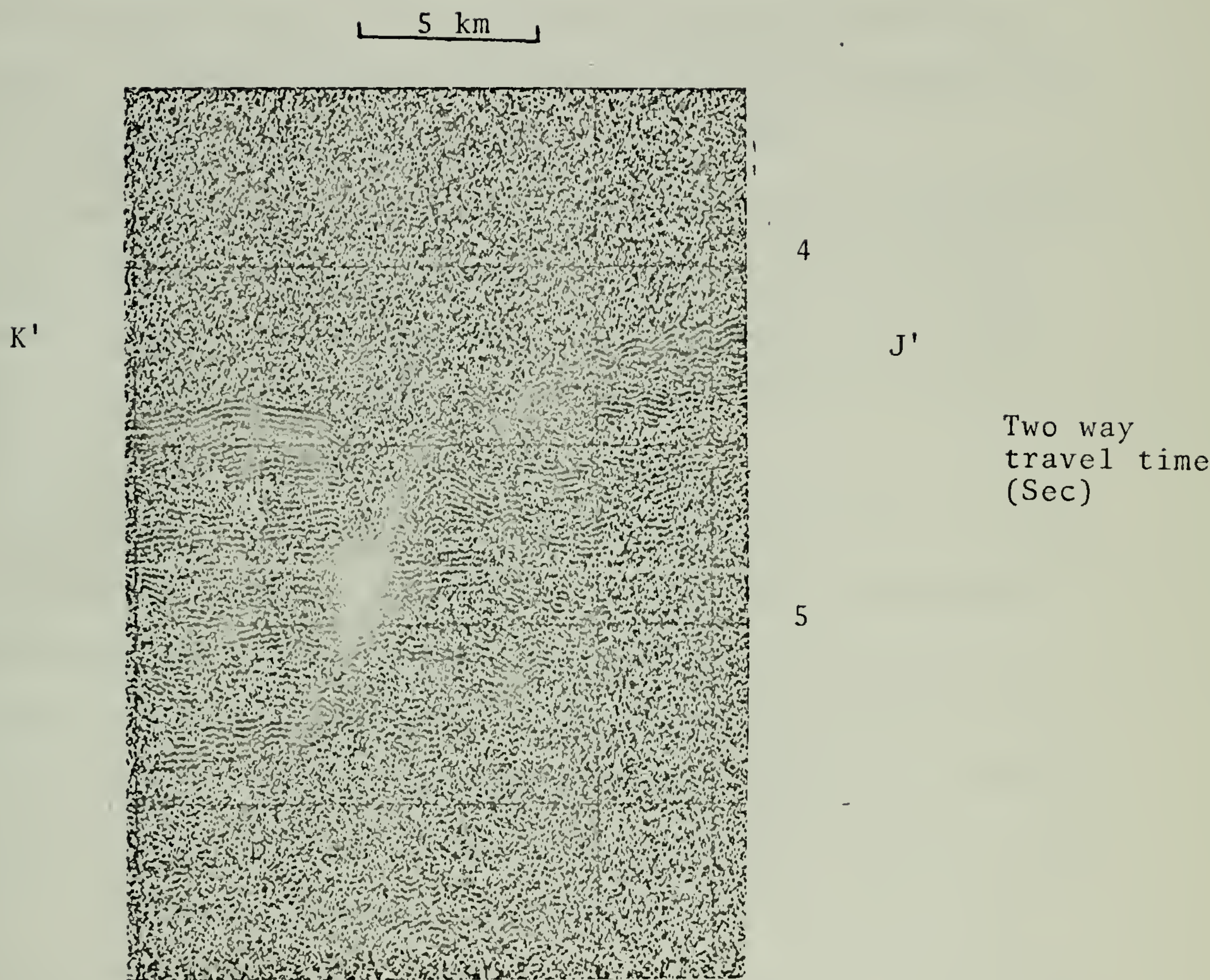

Figure 8 Seismic Reflection Profile J'-K'

already near base-level, the level below which a stream does not normally erode, then the only mechanism available for lowering its gradient is for it to become more sinuous. A stream in random turbulence will also tend to develop meanders. Once a meander has been formed the water will slope upward toward the concave bank and will tend to run downhill. A curve of comparable sinuosity and opposite curvature will form downstream (Gilluly, Waters, and Woodford, 1968).

There is not yet any theory or dynamic principle that quantitatively explains the characteristic geometric relations common to meandering channels (Leopold, Wolman, and Miller, 1964); however, it is probable that the same principles that apply to subaerial streams also apply to submarine channels formed by turbidity currents.

The processes associated with light bed loads are believed to apply to the Monterey Submarine Fan Valley. The proximity of the Ascension and Monterey Fan Valleys and their depositional nature could have combined to create a flat plain. If the Monterey Fan Valley was close to base-level (its head is the Monterey Submarine Canyon, cut through granite) then the only way for the channel to decrease its gradient was for it to become more sinuous. The tendency of the channel to lower its gradient proved to be stronger than the preferential sedimentation effect that opposes such a migration and probably explains why the channel migrated to the right at crossing I'-J' (Figure 7). The channel migration to the right at crossing J'-K' (Figure 8) is thought to be related to the horseshoe meander. After the occurence of the meander, this section of the channel migrated northward to its present position next to the left-hand levee of the Ascension Fan Valley.

D. ORIGIN OF THE HORSESHOE MEANDER

The absence of a well-defined left-hand levee across the head of the Monterey East Fan Valley suggests that it was once continuous with the Monterey Submarine Fan Valley. If this was the case, any overflow through the gap in the levee at that point would be rechannelized in the Monterey East Fan Valley and a levee would not have an opportunity to form. If the channels were not contemporaneous, then one would expect to find large levees across the head of the Monterey East Fan Valley as exist elsewhere in the meander. The relatively low relief of the Monterey East Fan Valley suggests that overflow from the present meander continues to add sediments to this area.

The horseshoe meander was probably formed by a combination of two mechanisms. The first was the tendency of the channel to decrease its gradient; and the second was a possible erosional break in the right-hand levee of the Monterey Fan Valley at its intersection with the Monterey East Fan Valley. This break would have allowed the turbidity current an exit from the channel and would explain the beheading of the Monterey East Fan Valley. It is also possible that the migration to the right in crossing I'-J' may have contributed to the meander's origin since one bend will tend to cause another one downstream in the opposite direction as described previously.

The downstream channel of the meander (crossing K'-L', Figure 9, which is looking south) migrated to its present position from a position beneath what is now the upstream channel of the meander. It is possible that a depression was left in the surface sediments as the channel migrated, and that the outbreaking turbidity current under the influence of this former track and the Coriolis force, was rechannelized for a

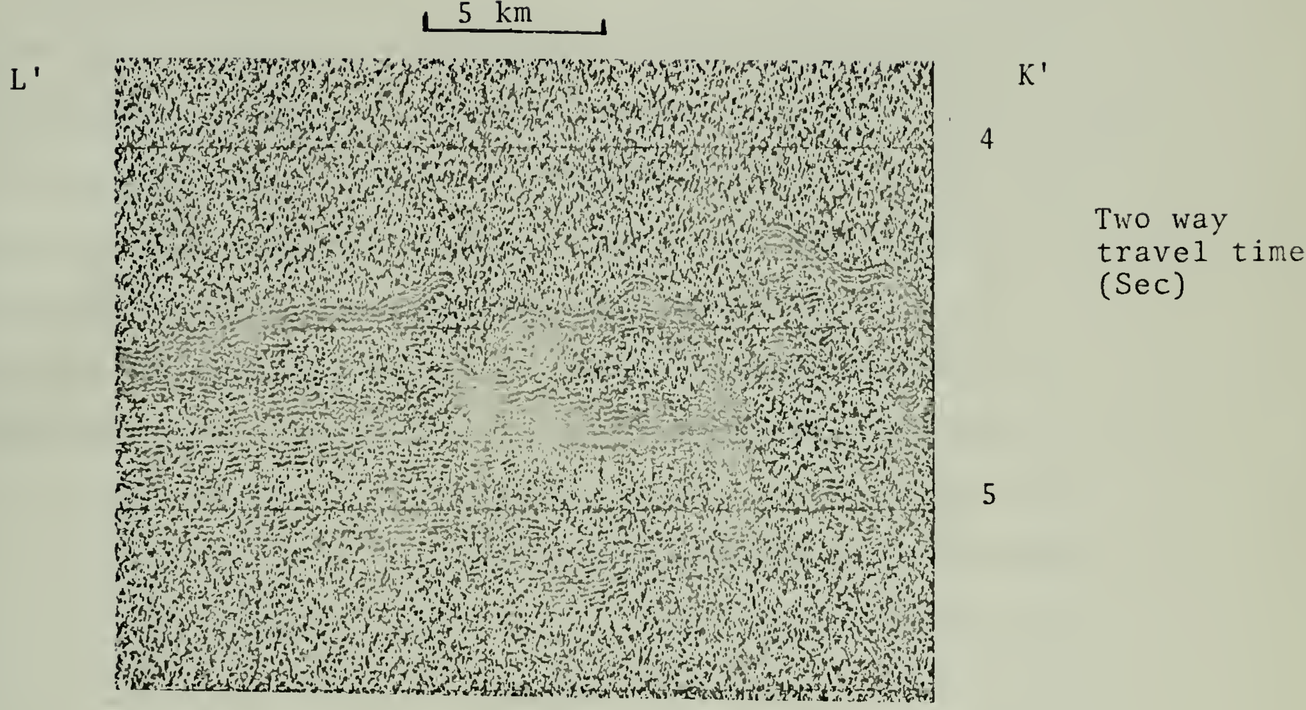

Figure 9 Seismic Reflection Profile K'-L'

short distance. It is believed that the current then turned to the west in an attempt to move parallel to the elevation contours until it flowed into the Ascension Fan Valley.

E. EROSIONAL ASPECTS OF THE MONTEREY SUBMARINE FAN VALLEY

The Monterey Submarine Fan Valley appears to have been erosional in the latter stages of its development. Most of the crossings at and below the meander show horizontal sediment layers out-cropping into the levee walls (Figure 8). If the Monterey East Fan Valley was once continuous with the Monterey Submarine Fan Valley, then extensive downcutting and some sidecutting must have created the relief now observed. Because the western levee of the Ascension Fan Valley is continuous with the western levee of the Monterey Fan Valley below their intersection and because there is no levee across the mouth of the Ascension Fan Valley nor evidence of levee growth in the sediments underlying this channel's mouth, it is believed that the Monterey Submarine Fan Valley pirated the lower half of the Ascension Fan Valley (Normark, 1969). If this is true, then extreme downcutting must have occured to leave the Ascension Fan Valley as a hanging valley. This downcutting could have occured as a result of erosion of the right-hand levee of the Monterey Fan Valley at the final bend in the meander. Normark (1969) suggested that the downcutting could have occured as a result in a change in the sea level, resulting in a change in the base level, or because of a change in the sediment transported by the turbidity current.

F. BASEMENT REFLECTIONS

Reflections from the basement were detected in crossings L'-M' (Figure 10) and M'-N' (Figure 11). The reflections were analyzed as being due to the basement because of their continuity, irregularity, and sharpness. The depth to the basement is about 0.5 sec one-way travel time (about 800 m). Using Menard's (1960) figures whereby he assumed an area of 2.4 x 10^4 km^3 for the total extent of submarine fans off central California and a sedimentary fill of 5.4 x 10^4 km^3, an average thickness of sediments of 255 m is found. The figure should be less than the actual depth of the basement since isostatic adjustment was not taken into account.

An interesting basement feature, possibly a ridge or a hill, is to be seen in section M'-N' (Figure 11). It is obvious that this feature has had an effect on the location of the Monterey Submarine Fan Valley though more information is needed to determine the exact effect. The origin and extent of the feature is not known, but it, and another similar basement feature 24 miles to the north, lies roughly on a line drawn through the Guide, Pioneer, and Davidson Seamounts (basalt volcanics), and may be related to them.

G. POSSIBLE FAULTS

Because of the diffractions present and the misalignment of the relatively horizontal layers, it is felt that a relatively recent fault may be observed in the records at latitude 36° 30.2' N, longitude 122° 45' W. As it is only seen in sections F'-G' (Figure 12) and G'-H' (Figure 13) near turning point G', no attempt was made to

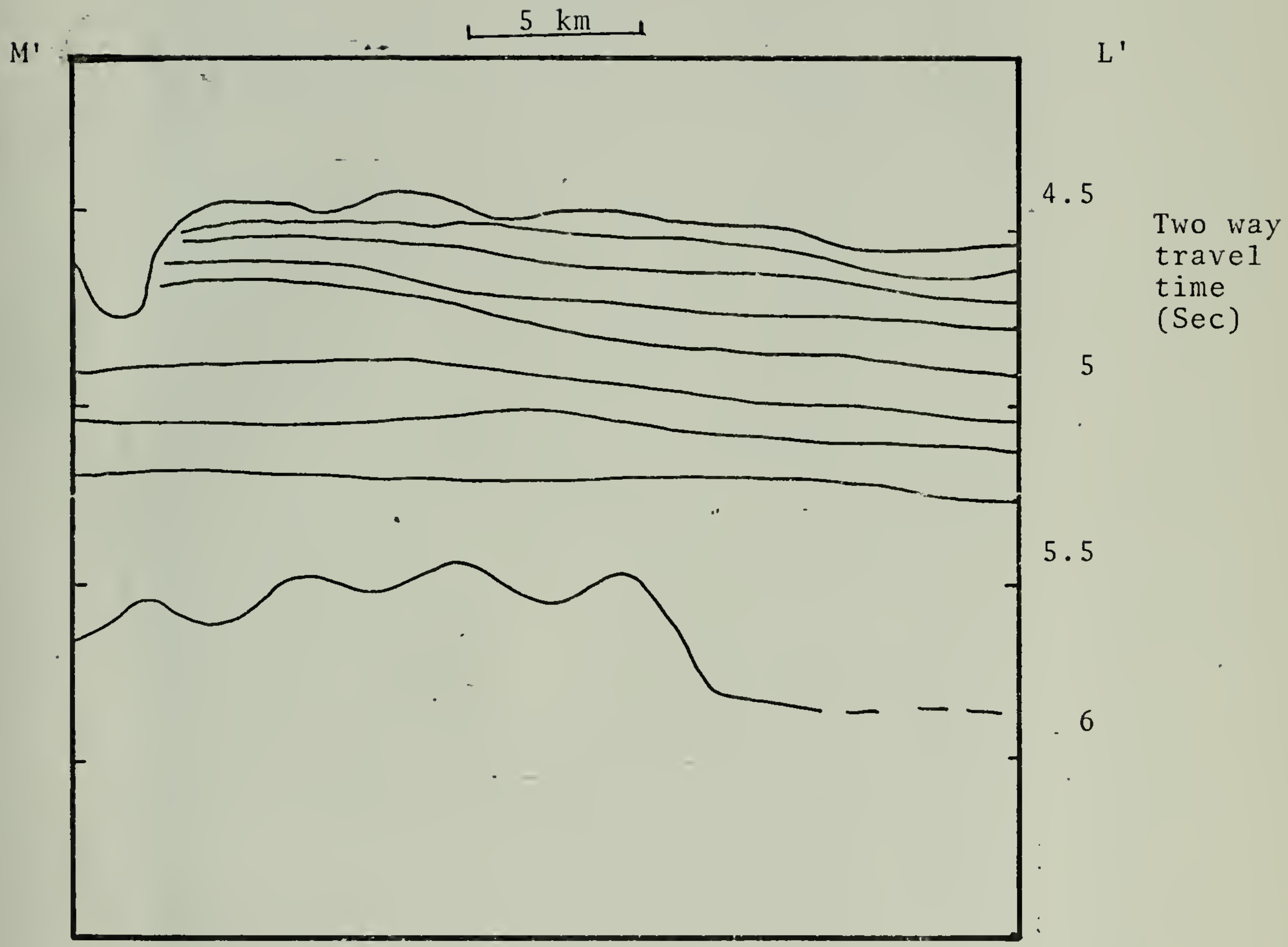

Figure 10 Interpretive Drawing of Seismic Reflection Profile L'-M'

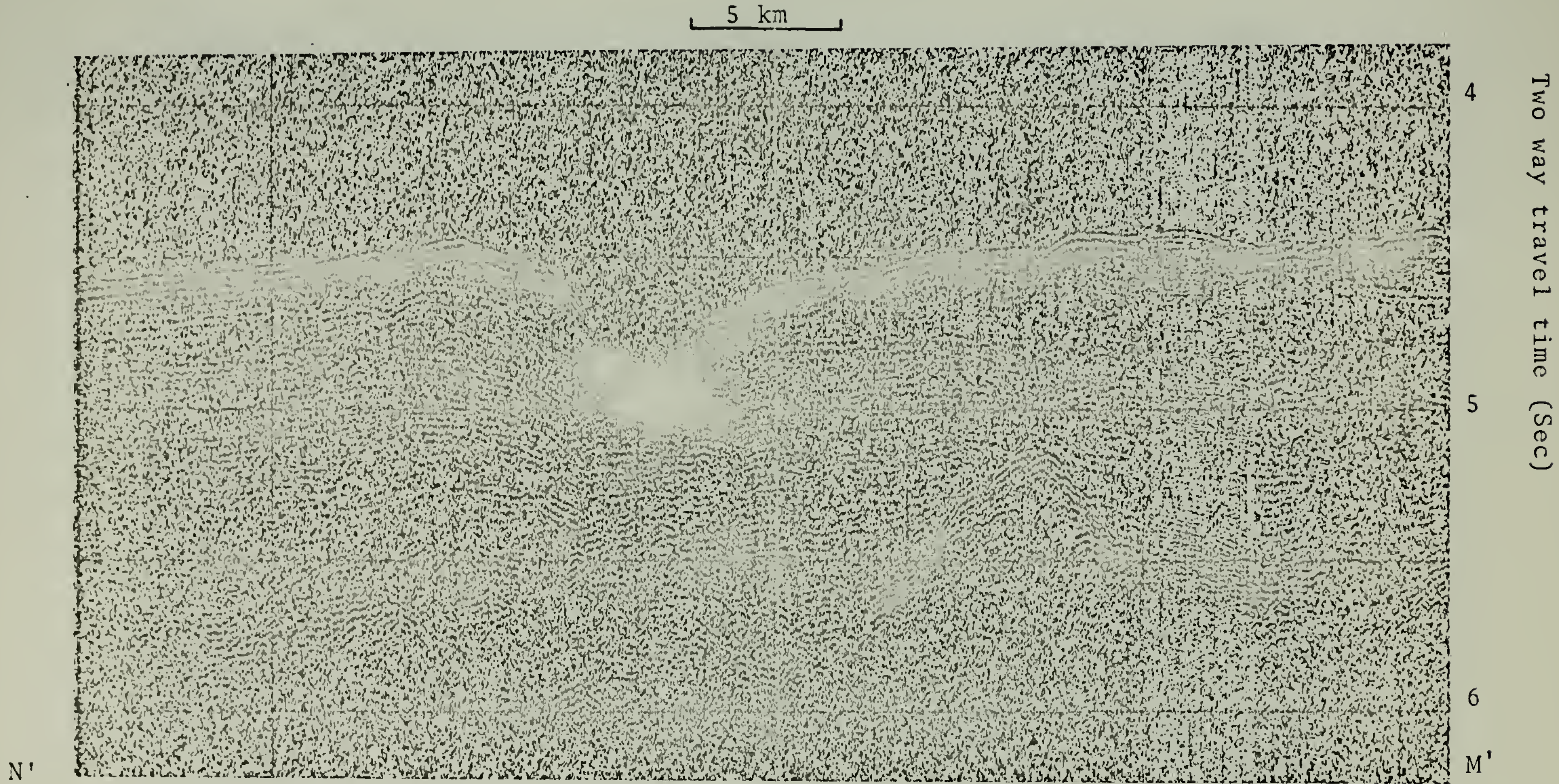

Figure 11 Seismic Reflection Profile M'-N'

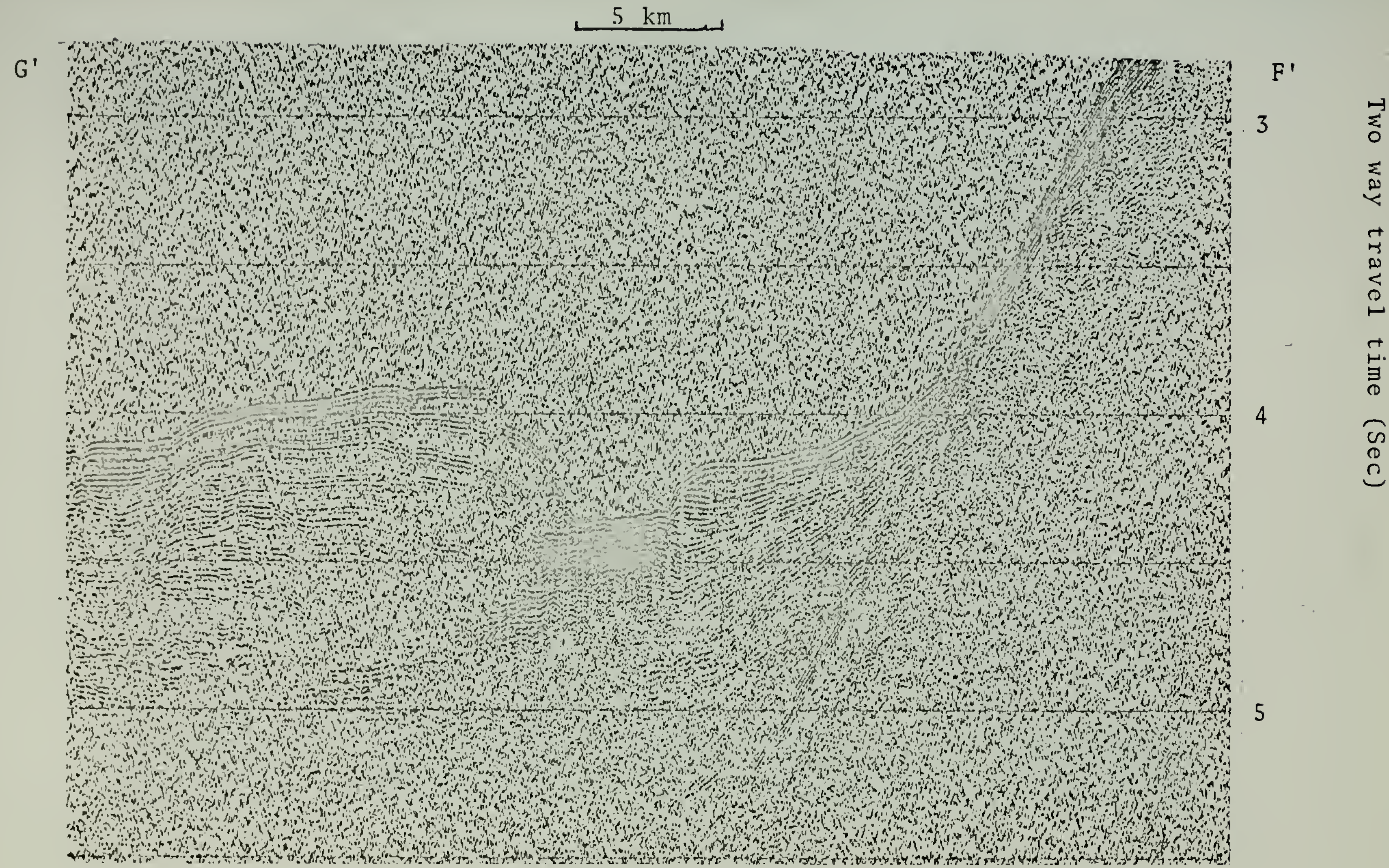

Figure 12 Seismic Reflection Profile F'-G'

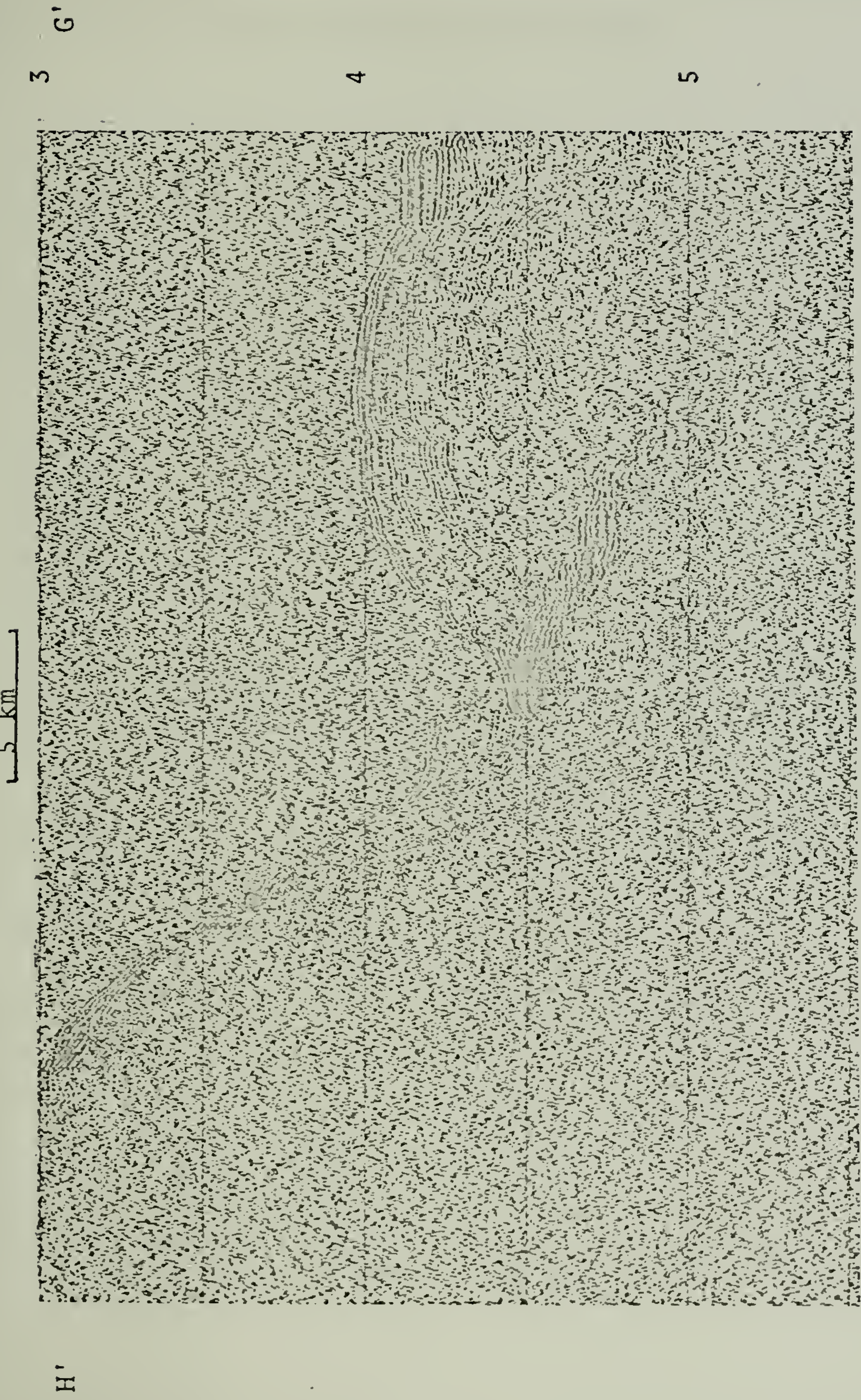

Figure 13 Seismic Reflection Profile G'-H'

trace it. Not enough information was available to determine what effect, if any, the fault has had on the channels.

IV. CONCLUSIONS

The flatness of the channel bottom of the Monterey Submarine Fan Valley is shown by the 3.5 kHz records. A bathymetric chart was constructed and compared to Shepard's (1966) bathymetric chart. The two agreed very closely. Any differences can be attributed largely to imprecise navigation.

The seismic records definitely show a channel migration by deposition. The migration has been primarily to the southeast (to the left downstream), with a few isolated cases where the channel migrated to the northwest (to the right downstream). It is believed that the channel migrated to the southeast because of the levee height difference resulting from preferential sedimentation by turbidity currents. The few migrations to the northwest were possibly attempts of the channel to decrease its gradient in much the same way a subaerial stream will develop meanders to decrease its gradient. It is felt that the horseshoe meander is related to this same mechanism and to the presence of the Ascension Fan Valley.

A secondary channel was observed beneath the western levee in three crossings of the upper Monterey Submarine Fan Valley. It is believed that this secondary channel and the Monterey Fan Valley had different sources of sediment. Approximately 1.9 million years ago the secondary channel was deprived of its sediment supply, possibly due to a change in the drainage patterns of the coastal region, and was subsequently filled by overflow from the Monterey Fan Valley.

The basement was noted on two crossings at about .5 sec one way travel time. This gives a sediment thickness of about 800 m.

V. FUTURE WORK

It is recommended that a seismic source with enough power to reach the basement along with a 6 sec firing rate be used to resurvey the area. Many more crossings of the Monterey Submarine Fan Valley are needed in order to definitely determine its history and structure. Some interesting basement features exist that should be thoroughly surveyed using gravimeters and magnetometers, in addition to the seismic equipment, so as to determine their extent and composition. The one fault which was noted should be further examined to determine its extent and possible effect on the Ascension and Monterey Submarine Fan Valleys.

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Structure of the upper Monterey Submarine Fan Valley.